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# TECHNICAL NOTE

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# POSSIBLE EFFECTS OF NONUNIFORM FLOWS ON PERFORMANCE OF ELECTROTHERMAL THRUSTORS

By John R. Jack and John W. Schaefer

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# POSSIBLE EFFECTS OF NONUNIFORM FLOWS ON PERFORMANCE OF ELECTROTHERMAL THRUSTORS

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## SUMMARY

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The effects of a nonuniform enthalpy profile on the performance of an electrothermal thrust generator have been evaluated analytically. Performance characteristics are presented for uniform specific impulses ranging from 1000 to 2000 seconds, pressures of 0.01 to 100 atmospheres, and engine wall temperatures of 500° and 3000° K.

The nonuniform profile changes the uniform specific impulse by 10 percent at most (except for simulated starting conditions), and the change can either be helpful or detrimental depending upon the specific operating conditions. In general, an increase in the engine wall temperature causes the specific impulse to approach the uniform flow value.

A very special nonuniform profile was also considered, one that may represent the startup of a cold engine. The magnitude of its effect on engine performance may be quite large, the variance depending on the operating conditions.

## INTRODUCTION

The usual performance analysis of an electrothermal engine is based on the assumption that the flow process is adiabatic and one-dimensional; however, in an effort to improve engine performance, plenum chambers have been eliminated (to reduce the total convective heat load), a swirling propellant flow has been utilized (to stabilize the arc and promote better mixing of the flow), and different arc geometries have been used (e.g., magnetically rotated arcs and constricted arcs). The net result of these changes and of the heat loss to the nozzle walls is a nozzle flow that is neither adiabatic nor one-dimensional, but usually has associated with it a severe enthalpy profile. This enthalpy profile should have some effect on the performance of an electrothermal engine.

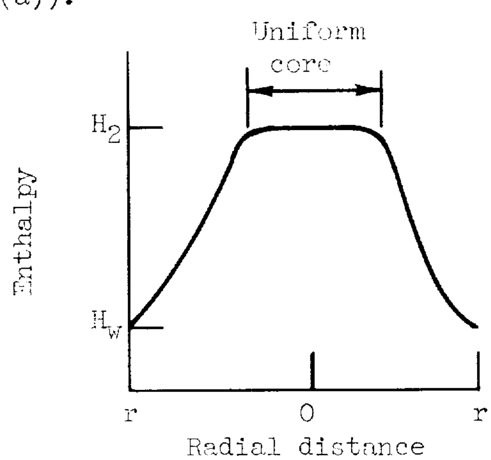
With the admission of an enthalpy profile, certain characteristics of it may be discussed. For example, the core enthalpy, which is generally uniform (ref. 1), must be high enough to yield the required engine specific impulse, whereas the value of the enthalpy at the nozzle wall can never be higher than that dictated by the maximum permissible nozzle-wall temperature. Thus, the propellant flowing in the jet core is characterized by very high stagnation enthalpies, while the flow surrounding the core is determined primarily by the nozzle cooling employed; it is quite low for liquid cooling and is moderate for radiation cooling.

If the flow in these thrust devices is almost frozen, the qualitative effect of the profile may be determined from the variation of frozen-flow specific impulse with stagnation enthalpy (ref. 2). In terms of the stagnation enthalpy profile, the propellant that passes through the jet core has associated with it a very high enthalpy corresponding to a specific impulse that may be as high as several thousand seconds. On the other hand, the flow surrounding the jet core has a low enthalpy, corresponding to a frozen-flow specific impulse of several hundred seconds. The problem, then, is to determine the effective specific impulse.

The effects of a nonuniform flow are discussed in references 3 and 4. The analysis of reference 3, however, is primarily qualitative while reference 4 considers only the effect of the boundary layer. The purpose of this paper is to present a more quantitative discussion of the effects of a nonuniform flow on the performance of electrothermal engines.

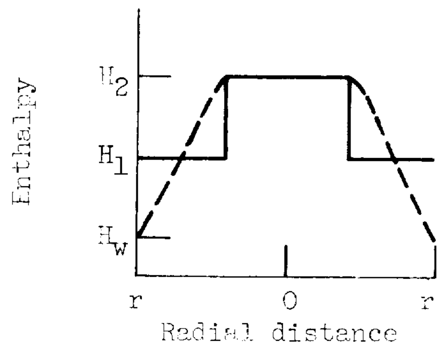
## ANALYSIS

If the effects of a nonuniform flow on frozen-flow engine performance are to be estimated, a model must be established for the enthalpy profile. As noted in the INTRODUCTION, the profile is characterized by a high core enthalpy $H_2$, which is generally uniform, and a wall enthalpy $H_w$ dictated by the engine cooling system (see sketch (a)).




(a)

(All symbols are defined in the appendix.) Enthalpy profiles very similar to that in sketch (a), with almost linear variations from $H_w$ to $H_2$, were observed in the investigation of reference 1. For simplicity of analysis, the profile considered herein (sketch (b)) consists of a uniform core at a value of $H_2$ and an annular region at a uniform average value of $H_1$.




(b)

The value of $H_1$ is defined as

$$H_1 = \frac{H_2 + H_w}{2} \tag{1}$$

With such a profile, the power in the propellant must be divided in the following fashion:

$$P_{gas} = P_1 + P_2 = \dot{w}_1 H_1 + \dot{w}_2 H_2 \tag{2}$$

The propellant flow rate must be given by

$$\dot{w} = \dot{w}_1 + \dot{w}_2 \tag{3}$$

Since the flow is assumed frozen and is divided into two regions, each having a different stagnation enthalpy, each region must have associated with it a certain amount of power that is available for thrust; or, each region must have associated with it a frozen-flow efficiency, since the frozen-flow efficiency is defined as the ratio of the power available for thrust to the total power in the propellant. Thus, the power available for thrust in the nonuniform-flow case is given by

$$P_A = \dot{w}_1 \eta_{F,1} H_1 + \dot{w}_2 \eta_{F,2} H_2 \tag{4}$$

where

$$\eta_{F,1} = 1 - \frac{P_{F,1}}{P_1}$$

$$\eta_{F,2} = 1 - \frac{P_{F,2}}{P_2}$$

The frozen-flow efficiency for each region is determined by the enthalpy ($H_1$ or $H_2$) and pressure. For the one-dimensional or uniform flow, the power available for thrust is given by

$$(P_A)_U = \dot{w}\eta_{F,gas}H_{gas} = \eta_{F,gas}P_{gas} \tag{5}$$

where $\eta_{F,gas}$ is determined by the uniform enthalpy $H_{gas}$ and the pressure. It is apparent from a comparison of equations (4) and (5) that, in general, $P_A \neq (P_A)_U$.

A convenient basis for comparing the uniform with the nonuniform case may be established by expressing equation (4) in terms of an effective frozen-flow efficiency and the gas enthalpy so as to have a form similar to equation (5). In terms of an effective frozen-flow efficiency, equation (4) becomes

$$P_A = \dot{w}\eta_{F,eff}H_{gas} \tag{6}$$

where

$$\eta_{F,eff} = \eta_{F,1}\frac{\dot{w}_1}{\dot{w}}\frac{H_1}{H_{gas}} + \eta_{F,2}\frac{\dot{w}_2}{\dot{w}}\frac{H_2}{H_{gas}} \tag{7}$$

Thus, the effective frozen-flow efficiency is a function of the respective frozen-flow efficiencies $\eta_{F,1}$ and $\eta_{F,2}$, but, in addition, it varies with the fraction of the total gas power in the profile regions 1 and 2. From equations (2) and (7), the effective frozen-flow efficiency may also be expressed as

$$\eta_{F,eff} = \eta_{F,1} - (\eta_{F,1} - \eta_{F,2})\frac{P_2}{P_{gas}} \tag{8}$$

where

$$\frac{P_2}{P_{gas}} = \frac{\dot{w}_2}{\dot{w}}\frac{H_2}{H_{gas}}$$

Equations (1), (2), and (3) yield the following expression for $H_2/H_{gas}$ in terms of $\dot{w}_2/\dot{w}$ and $H_w/H_{gas}$:

$$\frac{H_2}{H_{gas}} = \frac{2 - \left(1 - \frac{\dot{w}_2}{\dot{w}}\right)\frac{H_w}{H_{gas}}}{1 + \frac{\dot{w}_2}{\dot{w}}} \tag{9}$$

Sufficient equations are now available to evaluate the effect of a nonuniform flow on engine performance.

When a nonuniform velocity profile exists, the effective jet power (the power that defines the overall efficiency $\eta = P_{J,eff}/P_{gas}$) may be less than the power available for thrust as defined by equation (4) or (6). This may be substantiated by consideration of the following derivation. The effective jet power is given by

$$P_{J,eff} = \frac{F^2}{87\dot{w}} = \frac{\dot{w}I_{eff}^2}{87} \tag{10}$$

where

$$I_{eff} = \frac{F_1 + F_2}{\dot{w}} = \frac{\dot{w}_1}{\dot{w}} I_1 + \frac{\dot{w}_2}{\dot{w}} I_2 \tag{11}$$

For any frozen flow,

$$I = 9.33 \sqrt{\eta_F H} \tag{12}$$

Consequently, from equation (4), the power available for thrust becomes

$$P_A = \frac{\dot{w}_1 I_1^2 + \dot{w}_2 I_2^2}{87} \tag{13}$$

The ratio of these powers is

$$\frac{P_{J,eff}}{P_A} = \frac{\dot{w}_1^2 I_1^2 + 2\dot{w}_1\dot{w}_2 I_1 I_2 + \dot{w}_2^2 I_2^2}{\dot{w}_1^2 I_1^2 + \dot{w}_1\dot{w}_2\left(I_1^2 + I_2^2\right) + \dot{w}_2^2 I_2^2} \tag{14}$$

This ratio is less than unity because

$$(I_2 - I_1)^2 \equiv I_2^2 + I_1^2 - 2I_1 I_2 > 0$$

or

$$I_2^2 + I_1^2 > 2I_1 I_2$$

It is to be noted, however, that, if the flow is uniform ($I_1 = I_2$), this ratio is equal to 1, and there is no power loss.

This inefficiency in power conversion is usually not large but must be considered in determining an overall efficiency. Thus, the overall efficiency for the nonuniform-flow case may be expressed as

$$\eta = \frac{P_A}{P_{gas}} \frac{P_{J,eff}}{P_A} = \eta_{F,eff}\eta_P \tag{15}$$

where $\eta_P$ is a power-utilization efficiency defined as

$$\eta_P = \frac{P_{J,eff}}{P_A} = \frac{I_{eff}^2}{87\eta_{F,eff}H_{gas}} \tag{16}$$

For the case of a uniform frozen flow, the overall efficiency is simply the frozen-flow efficiency; consequently, the ratio of efficiencies (nonuniform to uniform) is given by

$$\frac{\eta}{\eta_U} = \frac{\eta_{F,eff}\eta_P}{\eta_{F,gas}} = \left(\frac{I_{eff}}{I_U}\right)^2 \tag{17}$$

where $I_U = 9.33\sqrt{\eta_{F,gas}H_{gas}}$ and $I_{eff}$ is defined by equation (11). The ratio of the nonuniform to uniform specific impulse is simply given by

$$\frac{I_{eff}}{I_U} = \left(1 - \frac{\dot{w}_2}{\dot{w}}\right)\frac{I_1}{I_U} + \frac{\dot{w}_2}{\dot{w}}\frac{I_2}{I_U} \tag{18}$$

This ratio will be used as the performance figure of merit in comparing a nonuniform flow with a uniform flow.

## CALCULATION PROCEDURE

The effect of a nonuniform enthalpy profile on engine performance may now be found by specifying the following parameters: gas enthalpy $H_{gas}$, wall enthalpy $H_w$, and fraction of the total propellant flow rate in the high enthalpy or core region $\dot{w}_2/\dot{w}$. In addition, it is specified that both flow cases (uniform and nonuniform) have the same stagnation pressure and total propellant flow rate.

With the specified parameters, the core enthalpy $H_2$ is obtained from equation (9). (This, in turn, makes it possible to find the fraction of the total power in the core region $P_2/P_{gas}$.) Next, the enthalpy of the outer annular region $H_1$ is found from equation (1). With $H_1$ and $H_2$ determined, the frozen-flow efficiencies ($\eta_{F,1}$ and $\eta_{F,2}$) for both regions may be obtained from figure 1. The data of reference 5 have been used to obtain figure 1. Sufficient information is now available to calculate the effective specific impulse. The effective frozen-flow efficiency is obtained from equation (7) and the effective specific impulse from equation (11). The uniform-frozen-flow efficiency $\eta_{F,gas}$ is determined from figure 1 at $H_{gas}$. Finally, the specific-impulse ratio may be calculated from equation (18).

By the procedure just outlined and with the assumptions and relations described in the previous sections, the effect of a nonuniform enthalpy profile on frozen-flow engine performance has been computed for the desired combination of variables. The following values and ranges of variables have been used:

| | |
|---|---|
| Propellant . . . . . . . . . . . . . . . . . . . . . . . . . . . . . | Hydrogen |
| Uniform gas enthalpy, $H_{gas,U}$, cal/g . . . . . . . . . . . . . . . | 12,000 to 120,000 |
| Uniform specific impulse, $I_U$, sec . . . . . . . . . . . . . . | 1000, 1500, and 2000 |
| Stagnation pressure, $p_0$, atm . . . . . . . . . . . . . . . . . . . | 0.01, 1, and 100 |
| Wall temperature, $T_w$, °K . . . . . . . . . . . . . . . . . . . . . | 500 and 3000 |

These parameters are typical of those to be expected for electrothermal propulsion devices. The wall temperatures chosen should approximate those obtained for liquid-cooled engines ($500^\circ$ K) and radiation-cooled engines ($3000^\circ$ K).

## RESULTS AND DISCUSSION

The results to be presented describe the effects of a nonuniform enthalpy profile on the frozen-flow performance of an electrothermal engine utilizing hydrogen for a propellant. In addition to the assumption concerning the shape of the profile, it is also assumed that the flow is frozen at stagnation conditions and that this represents the only power loss. Other losses, such as those due to heat transfer and expansion, have not been considered. For this reason, absolute values of specific impulse calculated by the method presented herein should be optimistic. The ratio of the nonuniform to uniform specific impulse that is presented, however, should be relatively unaffected by these additional losses.

### Hydrogen Frozen-Flow Efficiencies

Frozen-flow efficiencies for hydrogen are presented in figure 1 for pressures of 0.01, 1, and 100 atmospheres and for gas enthalpies as high as $2\times10^6$ calories per gram. The thermodynamic data of reference 5 were used to obtain these curves.

The shape of the curves may be explained as follows: as the gas enthalpy is increased, the frozen-flow efficiency initially decreases because of the dissociation of hydrogen molecules. As the gas enthalpy is increased further, the frozen-flow efficiency continues to decrease until the first minimum in the curve is reached. This point corresponds to almost complete dissociation. Any energy that is subsequently added to the gas is almost entirely absorbed by the thermal degrees of freedom of the hydrogen atoms so that the frozen-flow efficiency increases. A point is reached, however, at higher enthalpy, where ionization of the atoms starts. This point is near the first maximum in the curve. With sufficient ionization, the frozen-flow efficiency begins to decrease, since energy is being invested in the ionization process. Finally, the ionization process is complete, near the second minimum in the curve, and the frozen-flow efficiency again increases with increasing gas enthalpy.

The effect of pressure on frozen-flow efficiency is straightforward. The efficiency increases as the pressure increases because both dissociation and ionization are less at higher pressures.

### Effect of Nonuniform Flow

The effect of a nonuniform enthalpy profile on engine specific impulse is presented in figure 2 for pressures of 0.01, 1, and 100 atmospheres and wall temperatures of $500^\circ$ and $3000^\circ$ K. The former wall temperature is representative of values for a liquid-cooled engine, whereas the latter temperature is typical of values for a radiation-cooled engine. The reference uniform specific impulses that are used to establish a gas enthalpy level are 1000, 1500, and 2000 seconds.

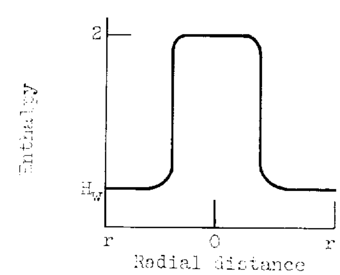
For a uniform specific impulse of 1000 seconds, the change in specific impulse due to a nonuniform enthalpy profile at all three pressures is limited to about 2 percent and the change in overall efficiency to about 5 percent (eq. (17)). This deviation from the uniform-flow case is inconsequential. The profile effect is mildly helpful at the lowest pressure considered, 0.01 atmosphere. For pressures of 1 and 100 atmospheres, specific impulse decreases slightly below that to be expected for a uniform profile. Curves for a wall temperature of 3000° K are not presented for $I_U = 1000$ seconds because the enthalpy associated with this temperature level is higher than that associated with a uniform specific impulse of 1000 seconds.

At a uniform specific impulse of 1500 and 2000 seconds, the profile effect is significant for certain conditions. For example, at $I = 1500$ seconds and $p_0 = 1$ atmosphere, the increase in specific impulse due to a nonuniform profile can be as large as 9 percent when the fraction of the total flow in the hot core is large. The overall efficiency can be as much as 19 percent higher at this condition. It should be observed, however, that the profile effect is different at other pressures. This behavior results from the nature of the hydrogen frozen-flow efficiency curves (fig. 1) and the variation of the two enthalpies $H_1$ and $H_2$ with $H_{gas}$. Note that at the lowest pressure a nonuniform profile may be helpful or harmful to engine performance, depending on the fraction of the total gas flow in the core region $\dot{w}_2/\dot{w}$. A similar behavior may be observed for $I_U = 2000$ seconds and $p_0 = 100$ atmospheres.

In general, an increase in the wall temperature causes the specific impulse ratio to approach 1, that is, to approach the uniform-flow case. The effect of a change in wall temperature on $I_{eff}/I_U$ is small, about 1 percent, except for a stagnation pressure of 0.01 atmosphere. At a pressure of 0.01 atmosphere the change in the specific-impulse ratio produced by an increase in the wall temperature is at most of the order of 5 percent.

## Special Nonuniform Enthalpy Profile

A special case of interest is that for which $H_1 \approx H_w$. The corresponding enthalpy profile is shown in sketch (c). This case may be typical of the




(c)

situation in which the engine has just been started at a cold temperature ($T_w \approx 500^{\circ}$ K). The results for this special case are presented in figure 3 for a pressure of 1 atmosphere.

For a uniform specific impulse of 1000 seconds, the profile effect decreases the thrustor performance considerably below that expected for a uniform flow. In fact, for $\dot{w}_2/\dot{w} \approx 0.10$, the specific impulse is lowered by over 40 percent, and the overall engine efficiency is about one-third of that expected for a uniform flow. The effect is generally detrimental at all impulses, although there is a small region of helpful effects for a specific impulse of 1500 seconds at $\dot{w}_2/\dot{w} > 0.80$.

## CONCLUDING REMARKS

A model for a nonuniform enthalpy profile has been proposed based on experimental observations. Its effects on thrustor efficiency and specific impulse have been determined for stagnation pressures of 0.01, 1, and 100 atmospheres, uniform specific impulses of 1000, 1500, and 2000 seconds, and wall temperatures of $500^{\circ}$ and $3000^{\circ}$ K. These operating conditions encompass most electrothermal-engine operating conditions of present day interest.

The effects of the nonuniform profile on specific impulse were at most of the order of 10 percent (except for simulated starting conditions), and the effect was either helpful or detrimental to engine performance depending on the specific operating conditions. In general, an increase in the wall temperature caused the specific impulse to approach that for a uniform flow.

One specific type of nonuniform enthalpy profile was also considered, the case where $H_1 \approx H_w$, which may represent the startup of a cold electrothermal engine. The effect on specific impulse of this nonuniformity was generally detrimental, and the magnitude of the effect can be quite large.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 6, 1963

# APPENDIX - SYMBOLS

$F$ thrust

$H$ enthalpy

$I$ specific impulse

$P$ power

$p_0$ stagnation pressure

$r$ radius

$T$ temperature

$\dot{w}$ propellant flow rate

$\eta$ efficiency

Subscripts:

$A$ available

eff effective

$F$ frozen flow

gas propellant

$J$ jet

$U$ uniform

$w$ engine wall

1 annular region

2 core region

## REFERENCES


1. Warren, W. R., and Diaconis, N. S.: Air Arc Simulation of Hypersonic Environments. Preprint 1986-61, Am. Rocket Soc., Inc., 1961.

2. Jack, John R.: Theoretical Performance of Propellants Suitable for Electrothermal Jet Engines. NASA TN D-682, 1961.

3. John, R. R., Chen, M., Connors, J. F., and Megrue, J.: Arc Jet Engine Performance - Experiment and Theory, pt. IV. Preprint 2345-62, Am. Rocket Soc., Inc., 1962.

4. Ghai, M. L.: Electrothermal Propulsion - Problems and Progress. Preprint 2348-62, Am. Rocket Soc., Inc., 1962.

5. Rosenbaum, Burt M., and Levitt, Leo: Thermodynamic Properties of Hydrogen from Room Temperature to 100,000° K. NASA TN D-1107, 1962.

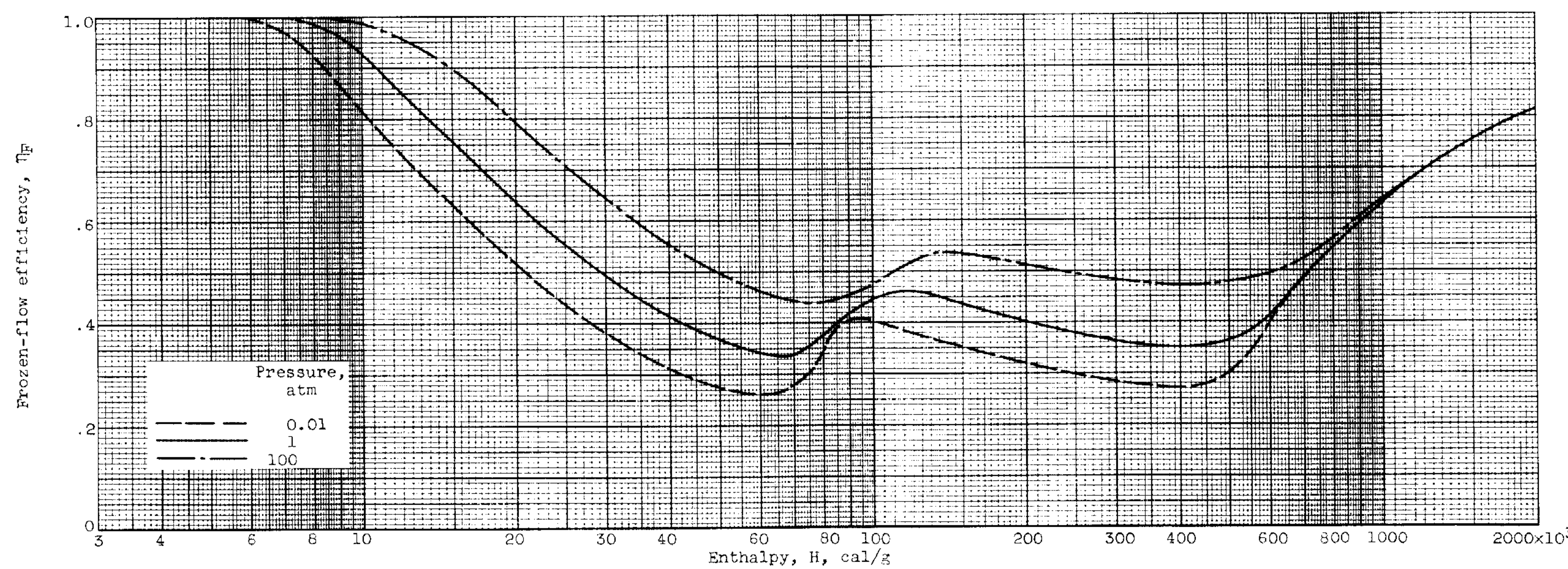
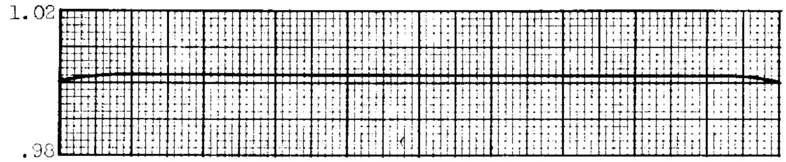
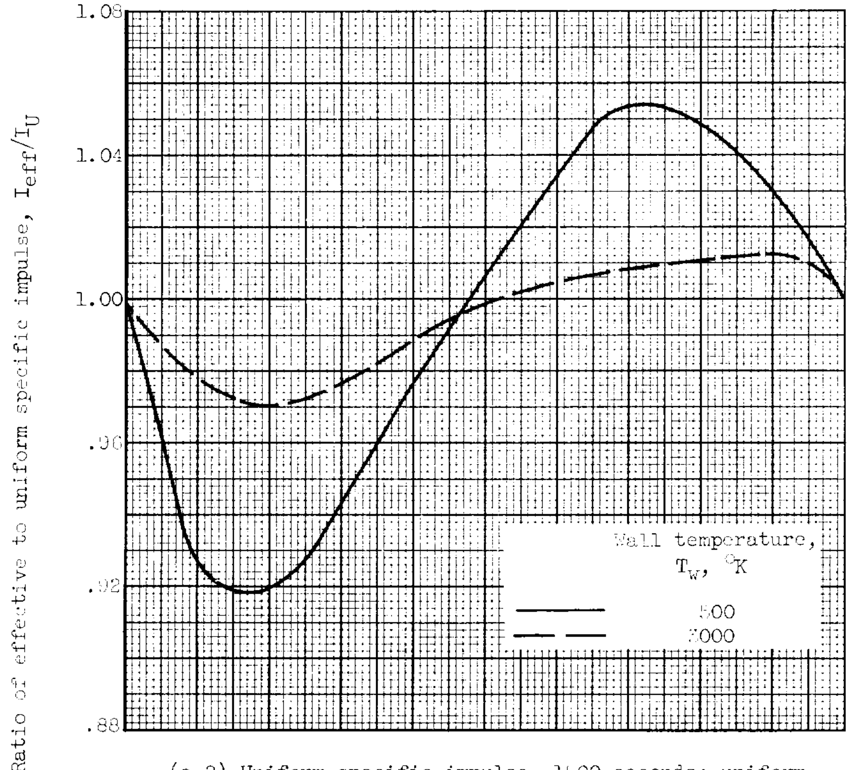


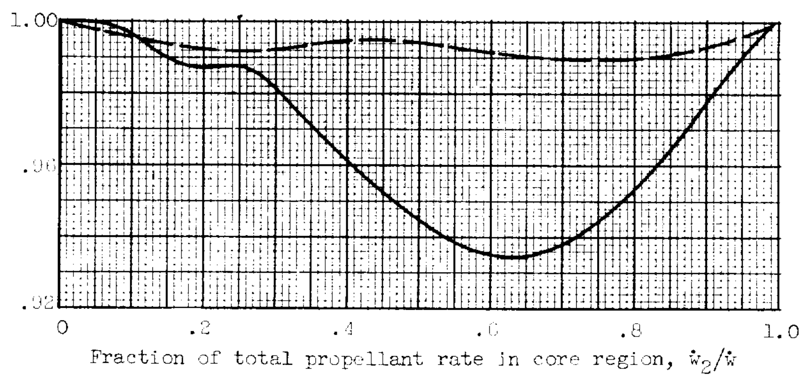

Figure 1. - Frozen-flow efficiency for hydrogen.




(a-1) Uniform specific impulse, 1000 seconds; uniform enthalpy, $30 \times 10^3$ calories per gram.



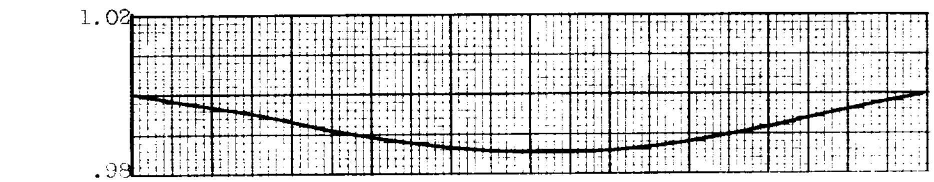

(a-2) Uniform specific impulse, 1500 seconds; uniform enthalpy, $77.4 \times 10^3$ calories per gram.



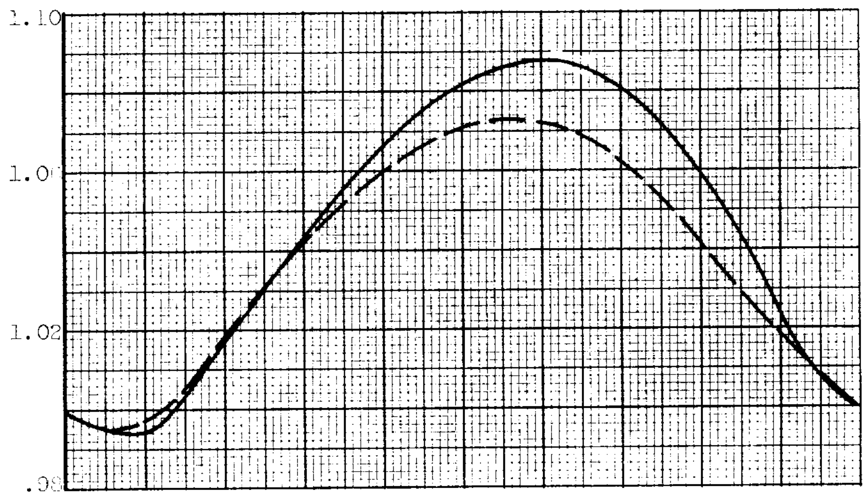

(a-3) Uniform specific impulse, 2000 seconds; uniform enthalpy, $120 \times 10^3$ calories per gram.

(a) Pressure, 0.01 atmosphere.

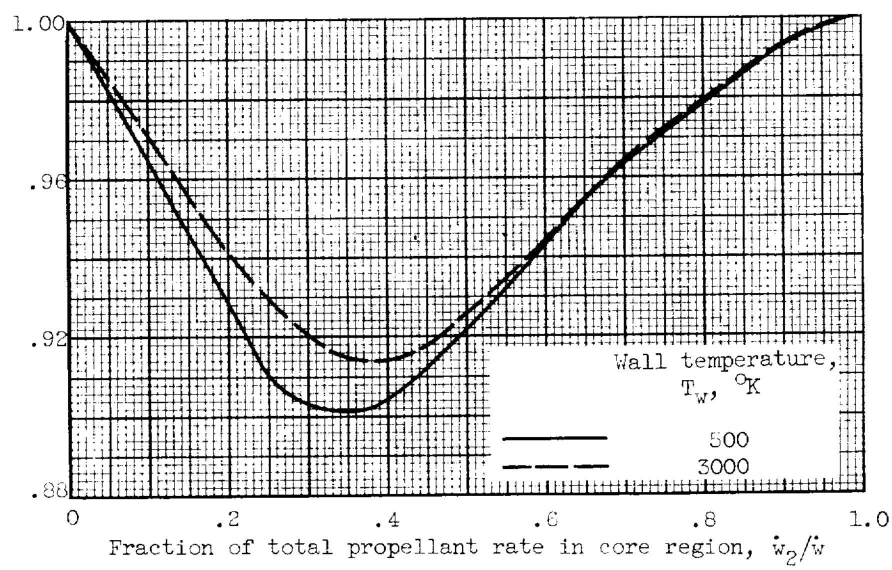
Figure 2. - Effect of nonuniform flow on specific impulse.




(b-1) Uniform specific impulse, 1000 seconds; uniform enthalpy, $15.3 \times 10^3$ calories per gram.



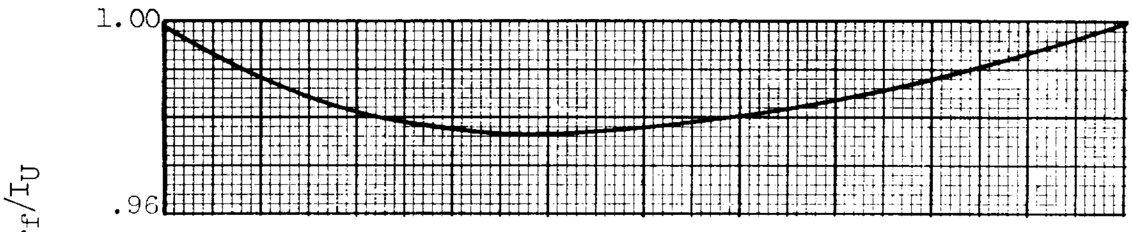

(b-2) Uniform specific impulse, 1500 seconds; uniform enthalpy, $76 \times 10^3$ calories per gram.



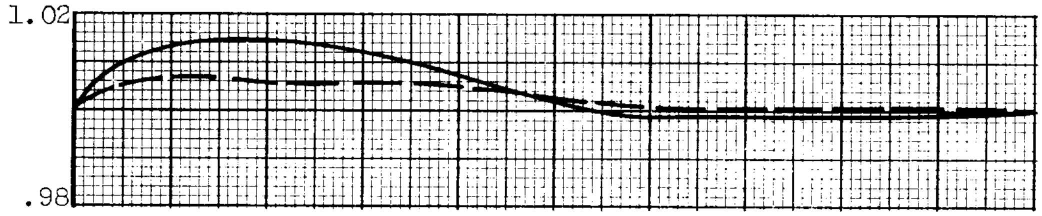

(b-3) Uniform specific impulse, 2000 seconds; uniform enthalpy, $101 \times 10^3$ calories per gram.

(b) Pressure, 1 atmosphere.

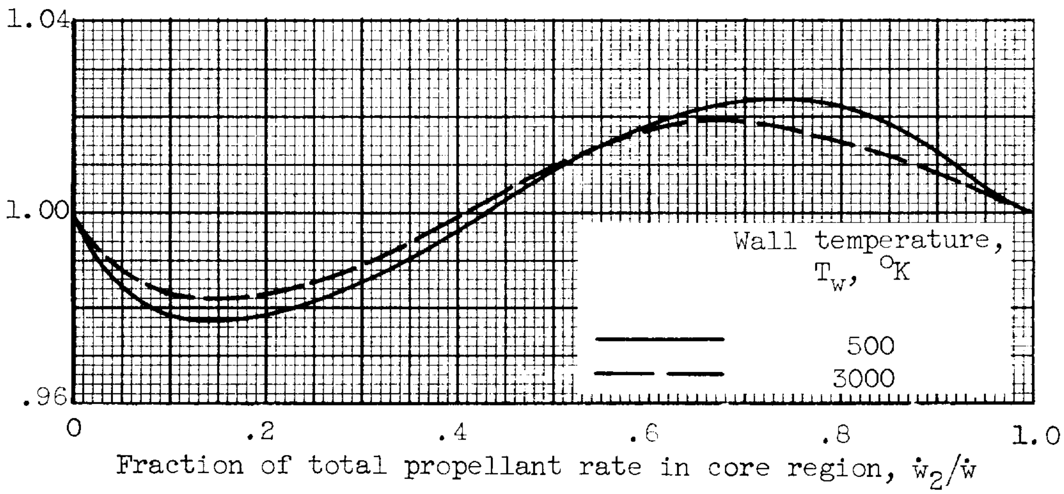
Figure 2. - Continued. Effect of nonuniform flow on specific impulse.




(c-1) Uniform specific impulse, 1000 seconds; uniform enthalpy, $12 \times 10^3$ calories per gram.



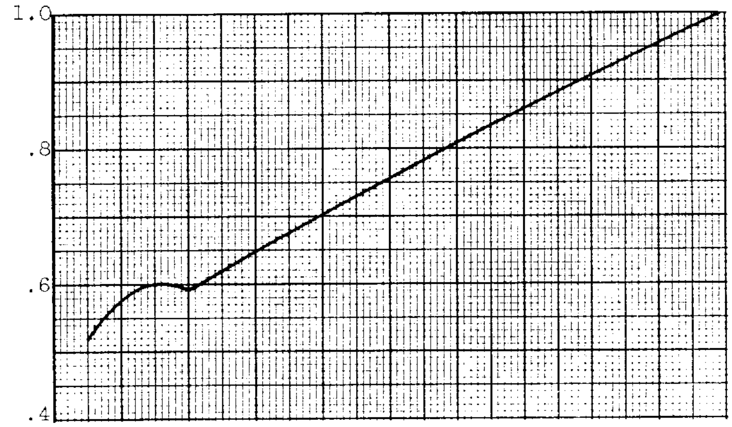

(c-2) Uniform specific impulse, 1500 seconds; uniform enthalpy, $53.3 \times 10^3$ calories per gram.



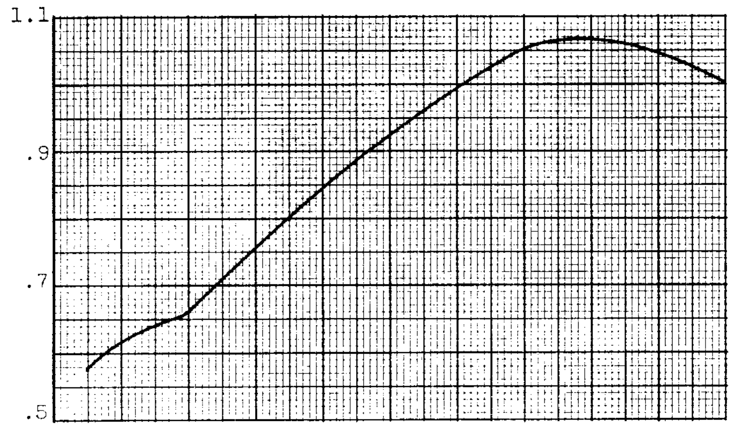

(c-3) Uniform specific impulse, 2000 seconds; uniform enthalpy, $97 \times 10^3$ calories per gram.

(c) Pressure, 100 atmospheres.

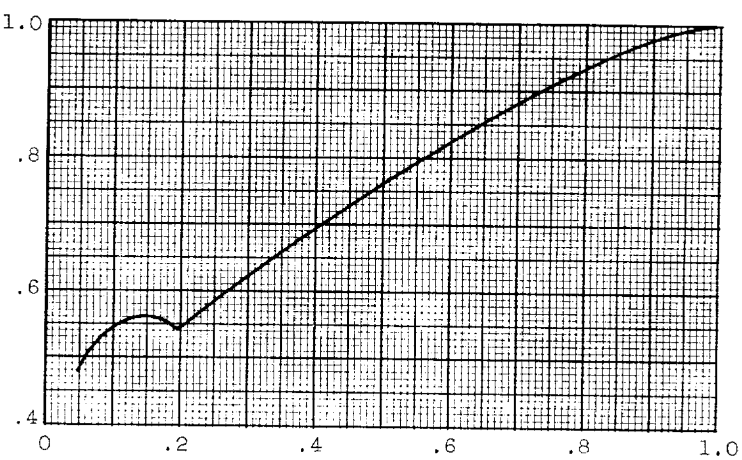
Figure 2. - Concluded. Effect of nonuniform flow on specific impulse.




(a) Uniform specific impulse, 1000 seconds; uniform enthalpy, $15.3 \times 10^3$ calories per gram.




(b) Uniform specific impulse, 1500 seconds; uniform enthalpy, $76 \times 10^3$ calories per gram.




(c) Uniform specific impulse, 2000 seconds; uniform enthalpy, $101 \times 10^3$ calories per gram.

Figure 3. - Effect of nonuniform flow on specific impulse when annular-region and engine-wall enthalpies are equal. Pressure, 1 atmosphere; wall temperature, 500° K.



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